Global and Regional Wave Modeling Activities

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Introduction

On any given day Naval vessels travel the world's oceans, nearshore exercises take place, and at times, real operations occur where lives and equipment are in harm's way. Accurately predicting environmental conditions such as meteorology (winds, temperature, moisture), oceanography (thermal gradients, currents, surges), and wave conditions becomes the governing factor for ship routing activities, and success of an exercise or operation often depends on minimizing the impact of these uncontrollable conditions. The other necessary factor governing the success of a forecast is providing the information in a timely manner. No matter how accurate the final wind, wave, and current predictions are, if the fleet does not receive this information before it occurs, it becomes irrelevant. This is defined as perishable information, where on a daily basis new forecasts are performed replacing the old (six- to twelve-hour) information.

Battles during World War II showed the need for reliable weather forecasts was essential. D-Day, the invasion of Normandy, is an excellent example of this. In the 1940s, all forecasting was performed manually. Sophisticated satellite data, cloud coverage, moisture content, Doppler radar, offshore meteorological buoys, or wave measurement devices did not become a reality for nearly 30 years. The decades that followed World War II through the space program saw the development of computers and the subsequent development of numerical models that were capable of predicting weather patterns. Fleet Numerical Meteorology and Oceanography Center (FNMOC) pioneered the wave-forecasting effort through the application of a parametric wave model in 1965 (Hubert, 1964), and a spectral wave model in the mid 1970s (Pierson, 1982). Through the Cold War years research developments in the field of air-sea interactions increased, focusing on improving environmental forecast modeling activities. Paralleling these activities, the development of large-scale computer systems was underway so that these new and more sophisticated models would provide timely forecast results.

To this date, the need for accurate and timely wave forecasts exists. Increased requirements by the U.S. military throughout the world have resulted in a threefold increase in the wave model resolution over the past 10 years. Requests by the U.S. military for littoral zone operations have become the mainstay for the Naval Oceanographic Office (NAVOCEANO) Warfighting Support Center (WSC) and are used in Logistics-Over-the-Shore Operations. In direct support of these operational needs, research activities supported by the Office of Naval Research (ONR) and the U.S. Army (Civil and Military Research Programs) develop, investigate, and improve existing and new wave-modeling capabilities. The motivation of these programs is cultivating new ideas in basic research activities focusing on strong theoretical foundations, incorporation of laboratory, and field investigations to quantify hypotheses. The results of the basic research are transformed into usable tools (e.g. computer routines) fostered in applied research. Ultimately these products are transitioned to the operational wave forecasting centers. The links between working groups and programs are critical. Feedback from the operational forecasting centers directly to the wave research community is key to the continual development of methodologies and the improvement in wave predictions.

Historical Perspective

The description of the ocean wave surface can be quantified as irregular and random (Figure 1). To model this random process, two distinct approaches can be applied. One is phase-resolving methods where the actual free surface (random and irregular) is solved using the continuity equation and equation of motion (Peregrine, 1967). Even with the most sophisticated and high-speed computational platforms, solution for a given domain is exceedingly laborious. This modeling effort requires accuracy levels that are of sub-wavelength scales. The second method, or phase-averaging approach, assumes the free surface can be described as a linear superposition of a finite number of wave energies defined in terms of the frequency and direction. Rather than solve for the time and spatial rate of change in the free surface directly, the free surface is described in the form of a directional wave spectrum (Figure 2). Modeling efforts dictated by spatial and temporal resolutions become more manageable within the context of a global domain. There is some loss in the description of the detailed structure of the free surface, however, this method has been used successfully for years.

Over the past five decades, wave-modeling technologies have steadily improved and increased in their relative complexities. In a pioneering effort based on theoretical and experimental work there was a direct relationship between the winds and surface-generated waves (Phillips, 1957). Bretschneider (1954) constructed nomograms relating fetch length and wind speed to estimate the significant wave height (H_s) and accompanying significant wave period (T_s). The term significant wave height was defined as the average of the highest ⅓ waves. The H_s is still used today, and proportional to the square root of the total energy a given wave spectrum, or:

$$H_s = 4 * \sqrt{\iint E(f,\theta)\, df d\theta} \qquad (1)$$

where $E(f,\theta)$ is the energy density spectrum, defined at each frequency band f and direction band θ. Modern-day advanced, wave-modeling technologies such as WAM (Komen et al., 1994) and WAVEWATCH III (Tolman, 1990) are used at weather prediction centers around the world.

The classifications have often times been termed first, second, and, third generation wave models. These wave models solve the action balance equation in some form. Action (or particle density in a classical physics framework) can be defined in the context of the ocean free surface, as the number of waves in a physical system. The action balance equation is given by:

$$\frac{\partial N}{\partial t} + C_g \cdot \nabla N = \sum_{i=1}^{n} S_i \qquad (2)$$

where N is the action density and equal to the energy density divided by the radial frequency ω, where $\omega = 2\pi f$ is a function of location (x,y), time (t), frequency (f) and direction (θ). C_g is the group speed dependent on the location x, y, of each frequency band, f. The source term expressed on the right-hand side of the equation is given by:

$$S_{total} = S_{in} + S_{nl} + S_{ds} + S_{w-b} + S_{br} \qquad (3)$$

The source-sink mechanisms describe the wind input term (S_{in}), the nonlinear wave-wave interaction (S_{nl}), and dissipation or *whitecapping* (S_{ds}). The atmospheric input source term is defined as the momentum transfer by the winds to the free surface. A portion of that momentum is transferred to wind-driven currents, and a portion is transferred to the wave field. This formulation scales to the square of the wind speed to the significant wave height or to the fourth power of the wind speed to the energy density. The nonlinear wave-wave interaction source function (Hasselmann, 1962) provides the means for energy to be transferred between frequency bands. It also was the principal mechanism for the downshifting of the peak frequency found in wind-generation wave-growth field studies (Hasselmann et al., 1973). The nonlinear wave-wave interaction source function conserves action energy and momentum. It moves energy primarily to the forward and rear face of the energy density spectrum. A schematic depicting the regions where the source terms are active in a frequency spectrum is found in Figure 3. Application of a spectral wave model in arbitrary water depths, wave-bottom effect (S_{w-b}), and depth-induced wave breaking (S_{br}) become active.

Numerically solving equation (2) for the time and spatial rate of change in action (or generally the two-dimensional wave spectrum) is performed in two parts. The time invariant portion of equation (2) is solved first for propagation of the energy in a fixed grid system. The spectrum in a numerical wave model is comprised

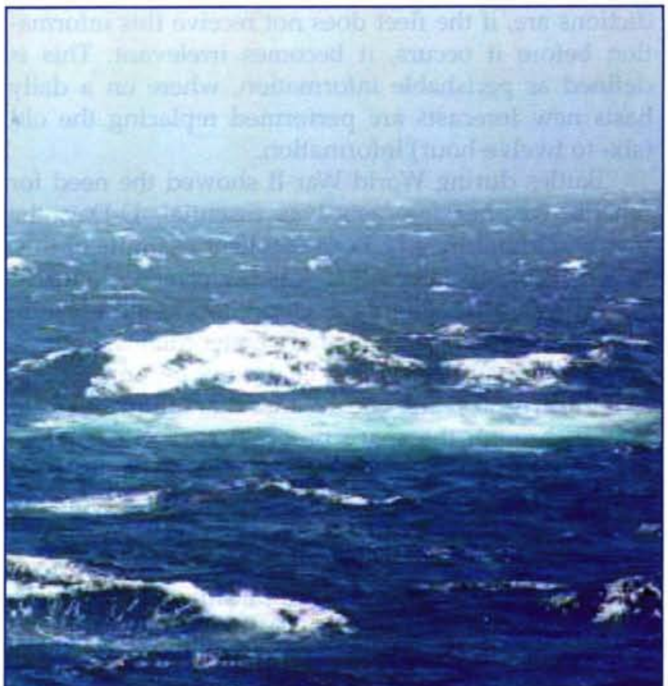

Figure 1. *Example of the randomness of the free surface.*

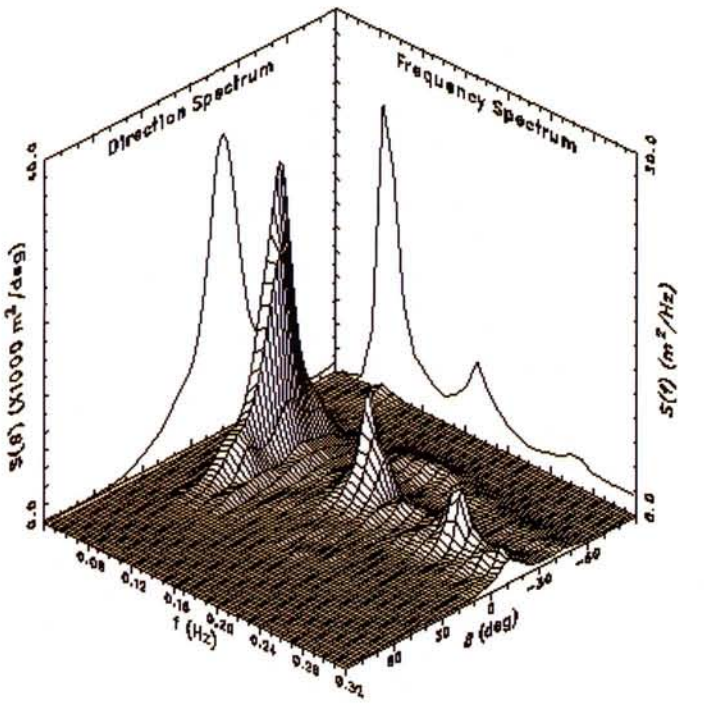

Figure 2. Directional wave spectrum.

of individual packets of energy (or action) described at each frequency and direction band. This solution assumes linear superposition of the energy, or each frequency, direction component can be treated independent of its neighbor. Once this step is performed, equation (2) is solved for the temporal change of action that is effected by the source terms found in the right-hand side of the equation. All wave models follow this procedure. The numerical integration of equation (2) may be different, or the description of energy rather than action is used. The difference between the class of wave models is dictated by what terms are represented in the right-hand side of the action balance equation, and how those relationships are solved. First-generation wave models included the atmospheric input and dissipation source terms. The S_{ds} was generally used at full development (Pierson and Moskowitz, 1964). This also controlled the growth of wind-generated wave conditions. Second-generation wave models (e.g. Sea Wave Modeling Project, SWAMP Group, 1985) include a parametric formulation of the nonlinear wave-wave interaction source function. One critical assumption governing second-generation wave modeling technologies was that the spectrum was to conform to some pre-determined shape in frequency and direction (e.g. JONSWAP spectral form, Hasselmann et al., 1973). Despite this limitation, well-tuned (generally to atmospheric models) second generation wave model results compared well to the increasing available wave measurements. One significant outcome of the SWAMP (SWAMP Group, 1985) was a rather large-scale discrepancy in wave height estimates for simple academic tests. It was concluded that the S_{nl} parameterization was the primary cause of the near order of magnitude differences found. The treatment of an extremely complex physical process was scaled to, at most, five parameters. Exact solutions were available in the 1980s (Hasselmann and Hasselmann, 1981), however, the computational requirements were orders of magnitude larger compared to those of the parametric formulations. Implementation of these exact solutions for S_{nl} in operational wave models was out of the question. The wave research community, under the direction of Professor Klaus Hasselmann formed a group (The Wave Modelling Group, Komen et al., 1994). Their goals were to overcome the deficiencies in second-generation models and implement a consistent set of source terms centered about a better formulation of S_{nl}, (Hasselmann and Hasselmann, 1985; Hasselmann et al., 1985).

Work on third-generation wave modeling technologies lasted for approximately 10 years, beginning with initial discussions starting in 1983. These models, for example WAM (WAMDI, 1988, Komen et al., 1994), WAVEWATCH (Tolman, 1990), and more recently SWAN (Booij et al., 1996), solve the source terms in discrete frequency and direction space. Nearly all world weather prediction centers presently use one of these models or a form of them.

Wave Modeling in the Navy Operational Forecasting Centers

The pioneering effort at FNMOC began in 1965 where a singular wave model (Hubert, 1964) was used. The Spectral Ocean Wave Model (SOWM) proved to be very useful, and reliable. SOWM was the first wave model that relied on wave growth theories of Miles (1957) and Phillips (1957) compared to purely empirical relation-based wave models. In 1973, the Mediterranean Spectral Ocean Wave Model (MED-SOWM) became operational, providing daily wave forecasts for the Navy (Lazanoff et al., 1973). The implementation of SOWM for the Northern Hemisphere (Lazanoff and Stevenson, 1975) followed in 1975. These achievements were significant milestones in the field of operational wave forecasting. FNMOC relied on this model for real-time wave forecasts and compiled one of the first wave climatological atlases used for ship design and planning purposes (Lazanoff and Stevenson, 1978). Despite its usefulness, SOWM suffered from inherent limitations. The implementation of SOWM covered only the Northern Hemisphere. The grid system selected proved to be a poor choice, and the propagation algorithm was awkward so that improvements/additions were limited in scope. This first-generation wave model ($S_{total} = S_{in} + S_{ds}$) served its purpose for nearly 10 years. Naval needs for global wave forecasting prompted work on SOWM's successor, the Global Spectral Ocean Wave Model (GSOWM). The source term physics were slightly modified (Cardone et al., 1976) in the formulation of the S_{ds} relationship. The most significant difference between GSOWM and its predecessor was in the propagation solution. The solution for propagation was based on linear superposition principles so that each energy component could be treated independently. A second-order numerical scheme, an energy-conserving downstream interpolation technique (Greenwood and Cardone, 1977), replaced the restrictive numerical solution method. The directional resolution describing the two-dimensional wave spectra was increased from 30° to 15°. The full implementation of GSOWM occurred in 1985. GSOWM was run on the standard FNMOC 2.5° longitude/latitude grid covering the globe from 77.5°N to 72.5°S latitude. The model was run four times per day, producing a 72-hour forecast on the 0000 UTC watch cycle and then a 48-hour forecast at the 1200 UTC watch cycle. The output from GSOWM was available for transmission to the fleet at 0600 UTC and 1800 UTC each day. During the off-watch hours of 0600 and 1800 UTC, GSOWM was run in a hindcast mode presetting the wave conditions for the next forecast cycle. This assured consistency and continuity between forecast sequences. The computational effort on 1980s architectures required approximately three minutes of processing time for a 72-hour wave forecast.

In the early 1970s, the number of point source measurements of wave characteristics was limited; however, this improved in the next decade. The National Oceanic and Atmospheric Administration's National Data Buoy Center (NDBC) maintained a number of offshore wave buoys (Hamilton, 1980). The buoy measured the free surface response and internally computed the frequency spectra. The significant wave height (H_s, or first moment wave height, H_{mo}) along with the peak wave frequency (f_m) was evaluated. Wind, pressure, and temperature sensors were located on each of the buoys, and the meteorological data were evaluated. The integral wave properties (H_s, and $T_p = 1/f_m$) were used in these evaluations. A series of metrics based on statistical testing of time-paired comparisons between model and measurements was performed (Clancy et al., 1986). The final wave model comparison and validation report concluded GSOWM was far superior to the results generated by SOWM.

The findings of this study also suggested one of the primary sources of error in the wave estimates to be in the modeled meteorological conditions. The link between errors in the atmospheric modeling techniques and wave estimates continues to present forecasting efforts. As atmospheric modeling research continues and improvements were made, wave model estimates would improve. This is based on scaling principles ($U^2 \approx H_{mo}$) between the wind speed (U) and the resultant significant wave height (H_{mo}). Over time and with continual verification of the wave model results, one can establish relationships between inherent wind-field errors and wave-model errors. If this bias persists for some time, corrections can be made to improve the resulting wave fields. Second-generation wave models use simplified source-term physics (compared to present third-generation wave models). This allows tuning persistent errors in the wind fields and reducing the overall bias in the wave model results. The downside of the strong dependency between atmospheric and wave models is that with every improvement to the atmospheric model, the wave model would need to be re-tuned. There are cases where

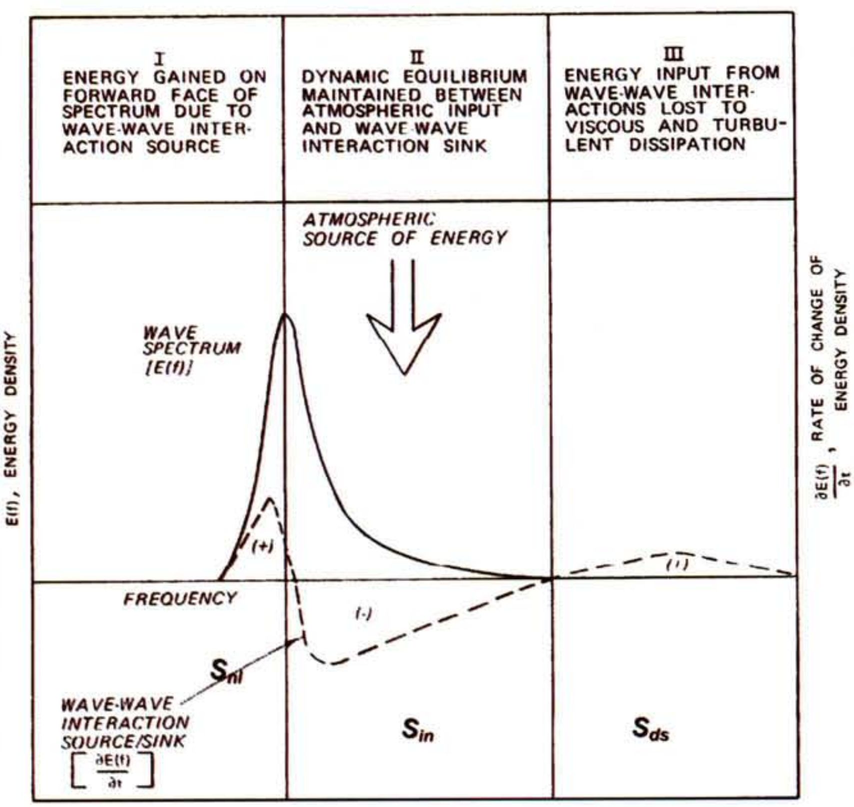

Figure 3. Regions in the frequency spectra where the source functions S_{in}, S_{nl} *and* S_{ds} *are active.*

first- and second-generation wave models outperform the more sophisticated third-generation technologies, (Cardone et al., 1996). Despite advancing the state-of-the-art, improved source-term physics, adopting better numerical schemes for wave propagation, the older wave models retain value and applications.

As FNMOC was completing the transition of GSOWM to operations, the wave modeling community was developing a community-based third-generation wave model called WAM (WAMDI, 1988; Komen et al., 1994). Testing of WAM was conducted at FNMOC as early as 1988 for the Mediterranean Sea. WAM replaced the first generation Mediterranean Sea SOWM in 1990 with increased number of frequency bands (from 15 to 25), and higher spatial resolution (from 0.66° to 0.50° and ultimately 0.25° in 1994). As MEDWAM provided a significant improvement to real-time wave forecasts, initial testing of WAM for global implementation was performed.

Two major impediments were facing a new global implementation of WAM at FNMOC. The first was an increased demand by the Navy for longer-range wave forecasts from the present 72-hour duration to 120-hour forecast. During this time, Naval global atmospheric modeling technologies were improving (see Rosmond et al., this issue) with increased spatial and temporal resolutions. Taking advantage of this, the resolution of the global wave model grid was increased from 2.5° to 1.0°. Any increase in the grid resolution generally is cubic in computational requirements, whereas extension of a forecast is linear. To meet the operational forecast scheduling requirements, FNMOC had to overcome a factor of 5.6 increase in computer resource demands. This was solved using Cray specific auto-tasking procedures, WAM internal vector processing capabilities, and high-speed, solid-state disks.

A four-month model comparison was made between GSOWM and WAM using NDBC buoy data. Testing of WAM and GSOWM followed similar procedures and evaluation used in previous model technology upgrades (Wittmann and Clancy, 1993; Wittmann et al. 1995). The general trend of the global WAM (GWAM) significantly reduced the bias in wave height for all domains (e.g. North Atlantic, U.S. East Coast, Gulf of Mexico, Gulf of Alaska, West Pacific, Hawaiian Islands). The bias in wave heights based on the composite data set from all domains was decreased to 0.09 meters using GWAM compared to 0.44 meters derived from GSOWM. The root-mean-square error also decreased from 0.94 meters to 0.70 meters. There was a tendency for a slight over-estimation in low H_{mo} conditions (< 1.5 meters), and an under-estimate of high H_{mo} results (> 7 meters). In general, overcoming the increased computational demands (with new hardware) and a significant improvement in the wave results using GWAM, FNMOC transitioned GWAM to operational state in 1994.

The GWAM wave forecast was run four times a day using FNMOC's Navy Operational Global Atmospheric Prediction System (NOGAPS, Rosmond, et al., this issue) surface wind-stress fields. A 144-hour wave forecast was performed at the 0000 UTC and 1200 UTC watch cycles. During the 0600 and 1800 UTC cycles, the global wave field was integrated to the next watch cycle with revised surface stress fields. The off watch cycle procedures maintained continuity in the wave field. These steps are critical to the wave forecast. The requirements to capture all wave energy in an ocean body at a specific location necessitate time for the winds to act on the sea surface. The Pacific Ocean generally takes a minimum of 10 to 15 days to assure all the energy from the Southern Ocean to be in the proper location in the northern Pacific. In the Atlantic Ocean requirements are about 5 to 10 days. Hence, losing the files containing directional spectra from the previous run would necessitate restarting the global wave forecast many days earlier to provide the time to build the proper energy in the domain. From 1994 GWAM has been running wave forecast operationally. Wave fields are distributed to the fleet now in graphical form similar to that shown in Figure 4.

A new focus for Naval warfare, from global threat to regional conflict, summarized in a September 1992 document, *"... From the Sea,"* co-authored by the Secretary of the Navy, the Chief of Naval Operations and the Commandant of the Marine Corps, stimulated work at the NAVOCEANO. The role of the NAVOCEANO's WSC was to supply the fleet with wave forecast estimates in marginal seas and semi-enclosed bodies of water. The accurate forecast of waves, currents, tides, water clarity and other environmental conditions was required to:

1. Put forces on the beach
2. Detect, track and remove mines and obstructions
3. Ensure trafficability ashore
4. Support special and anti-submarine warfare

In order to meet these new needs, wave modeling technologies originally designed for oceanic basins and deep water were to be adapted for smaller domains and increased grid resolutions, that are dependent on the offshore bathymetry. This effort would complement the role of FNMOC. The Navy Operational Regional Atmospheric Prediction System (NORAPS, Hodur, 1987), and more recently replaced with the Coupled Ocean/Atmospheric Mesoscale Prediction System (COAMPS, Hodur, et al., this issue), provided the wind-field forcing at the resolution required to model local effects.

The spectral wave forecasting system was developed and built around WAM at NAVOCEANO to meet the newly established littoral zone demands of the Navy. Selective Areas of Responsibility (AOR) corresponding to high-risk areas, were set up, tested, and evaluated. In general, the wave model's grid resolutions were nominally set at 0.25°, and the duration of the forecast period was originally set at 48-hours. The automated forecasting procedures were similar to those of FNMOC, and the output products, wave height, and direction fields were transmitted to the fleet.

WAM (Komen et al., 1994) was originally developed to nest selectively from low-resolution domains into higher resolution domains. This procedure was modified such that multiple boundary conditions could be generated from one GWAM simulation, thus significantly reducing the computational demands. The partnering of FNMOC, NAVOCEANO and research activities of the U.S. Army Corps of Engineers, Engineering Research and Development Center's (ERDC) Coastal and Hydraulics Laboratory (CHL) provided the means to accomplish this goal. WAM was tested and evaluated in data rich environments, for arbitrary water depths and a variety of meteorological storm scenarios (e.g., Jensen, 1995; Vincent and Jensen, 1996) to assure consistency and accuracy. The initial collaboration between research and operations strengthened into a working Army/Navy Wave Prediction Group (Su et al., 1996). This group stimulated new ideas, timely field experiments (e.g., the Shoaling Waves Experiment), and ONR's Advanced Wave Prediction Program (Vincent and Jensen, 1999).

During the mid 1990s, NAVOCEANO's WSC continued to add new AORs to their operational forecasting system (Figure 5). In addition to these continually operational domains, requests to support exercises and operations for a fixed time period necessitated the development of movable, site-specific high-resolution wave forecasting capabilities. Nominal grid resolutions were on the order of 5 minutes; however, some requirements dictated using grids of 1 minute. To meet the increased needs of littoral operations required grid resolutions to be on the order of hundreds of meters. In this context, bathymetric effects such as shoaling, refraction, wave-bottom effects, and ultimately depth-induced breaking become the controlling mechanisms to estimate coastal wave conditions. Presently STWAVE (Smith et al., 1999) has been used successfully by NAVOCEANO to forecast the wave conditions supporting

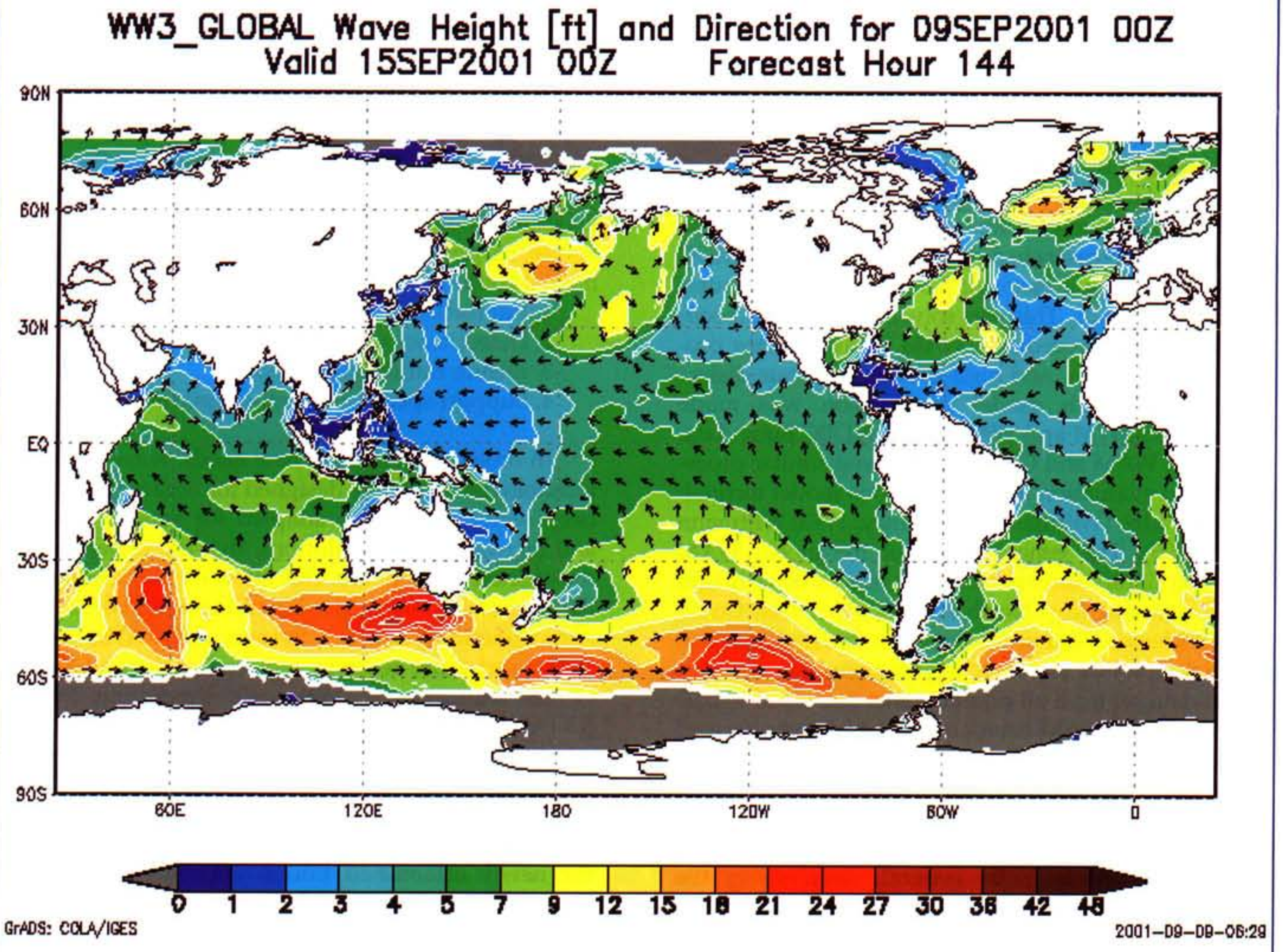

Figure 4. FNMOC's WAVEWATCH III wave height color contour plot (in feet). The vectors represent the mean wave direction.

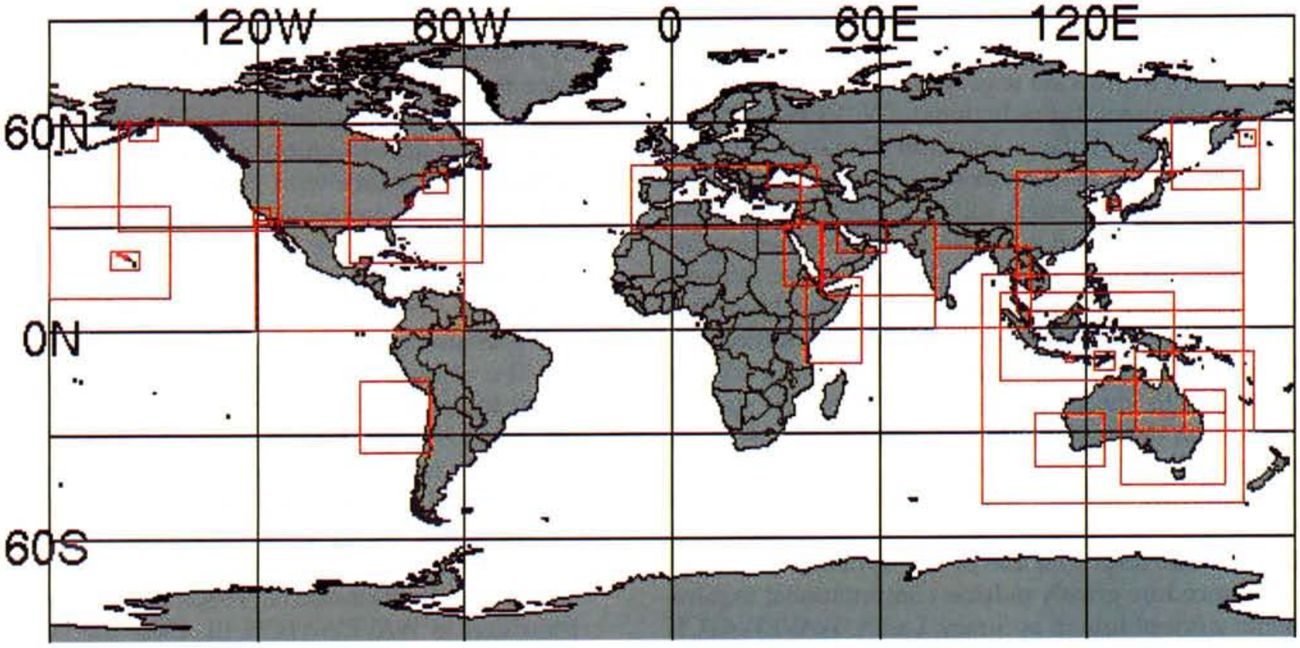

Figure 5. AORs, and ultra-high resolution WAM domains presently running operational wave forecasts at NAVOCEANO.

the ultra-high-resolution wave modeling domains. STWAVE is forced by directional wave spectra derived from the highest level WAM simulations at the offshore boundary. The spectra are propagated into the surf zone. The results from STWAVE were used for a Navy exercise as initial conditions to successfully drive a harbor response model. New advancements in wave modeling technologies such as SWAN (Booij et al., 1996) developed from the ONR's Advanced Wave Prediction Program will, in the future, supercede STWAVE.

Meeting the Operational Needs of the Navy in the 21 Century

Activities at FNMOC and NAVOCEANO's operational wave forecasting centers have placed an increased demand on their computer facilities. One of the largest concerns to FNMOC and NAVOCEANO today has been meeting the increasing requests from the fleet and maintaining timely, accurate wave-forecasting capabilities.

The increase of wave model grid resolutions, additional hot spots that directly support Naval exercises, and operations, place a significant burden on existing computer facilities. New computational architectures are replacing older systems at rates twice those of the past decade. To meet these new requirements, efforts were recently made to recast the wave modeling technologies into a framework so that transitioning to new computational platforms required a minimal effort. Use of parallel-processing in existing wave models became a necessity. Under the Department of Defense's Common High Performance Support Initiative, a project focusing on the migration of WAM to scalable computing environments was undertaken (West et al., 1997). WAM had the necessary requirements of a block/element structure and an explicit numerical scheme to perform domain decomposition, parsing the work to multiple processors. During the time of this work, new methods such as OpenMP, internal caching, and improved executable directives for parallelization were available. The importance of this work to the operational wave forecasting centers was critical and timely. NAVOCEANO was required to run, nominally, 45 WAM regional domains twice daily. To meet the existing needs, the forecasting technique runs WAM on two (small area domain) to four (large area domain) CPUs. The strategy is to avoid WAM simulations competing for the same resources, thus increasing overhead and significantly reducing throughput. Presently in an optimized and automated scheme, the complete NAVOCEANO operational wave forecasting system has been able provide over 100 WAM generated (AORs and ultra-high-resolution domains) sets of products to the fleet. The identical scalable version of WAM was transitioned to FNMOC in June 2000. Implementation of the parallel version of WAM encountered many added technological problems because of extensive internal modifications require for specific FNMOC wave-forecasting needs. Despite extensive redevelopment, testing, the performance of WAM in its scalable state could not be improved.

A new third-generation wave model called WAVEWATCH III (Tolman 1990; Tolman and Chalnikov, 1996) was being implemented at many weather prediction centers worldwide (e.g. NOAA's National Center for Environmental Predictions). WAVEWATCH III solves the action balance equation (Equation [1]). The source-sink term mechanisms are somewhat different from WAM. The greatest difference between the two models is in the third-order propagation scheme used by WAVEWATCH III. This higher order scheme responds better to long-range swell propagation than the first-order scheme used in WAM. In addition, the source term integration uses a time splitting scheme that reacts to low and high energy states. At specific locations in the domain where increased energy development takes place, the source term integration uses a fractional step method, where $\Delta t = 3\Delta t_{dynamic}$. For low wave-energy areas, the source term integration uses the full time step. The use of the dynamic time-stepping procedure greatly reduces computational requirements without loss in accuracy. Lastly, WAVEWATCH III is written with an added hierarchy in parallelization compared to that in the scalable version of WAM.

Over a two-year period, comparisons were made between GWAM and WAVEWATCH III for the global implementation. Using NOGAPS wind fields and comparing to satellite wave estimates, the improvement in wave estimates using WAVEWATCH III was apparent (Figure 6). Based on these comparisons (and to point source measurements), FNMOC has transitioned WAVEWATCH III to operations in August 2001.

Future Wave Research and its Role in Operational ForecastingOver the past decade, there has been an increased awareness in the research community of the needs of the Navy and its operational wave-forecasting centers. The flow of new research activities generally followed the path from basic to applied then transitioned to the operational centers like FNMOC and NAVOCEANO. What has been determined is that there is a feedback mechanism driven by the results in Figure 6 to drive new research activities in the Navy and the Army (Civil Works and Military). GWAM and WAVEWATCH III tend to underestimate the larger H_{mo} conditions greater than about 7 to 8 meters. Whether the cause for these misestimates are derived by poor atmospheric forcing or are regionally selective cannot be answered in one set of comparisons. However, when similar results appear, and the trends continue, it is generally hypothesized that the wave model and its scaling to the winds may be inappropriate for high wind cases. A new ONR research program called the Coupled Air-Sea Transfer is focusing on these issues, to improve the wave, ocean currents, and atmospheric modeling from new field data.

The amount of time provided to run wave forecasts at either FNMOC or NAVOCEANO is fixed and scheduled. If a given wave forecast exceeds the scheduled time, the information provided to the fleet could potentially be too old and of no use. New computer hardware now has a life span of about 3 to 5 years. Therefore new, faster platforms will become more readily available on the operational forecast floor. However, once these platforms become, for example eight-times faster, the forecasting centers could potentially increase their model grid resolutions by a factor of two. More sophisticated source-term physics could replace existing parametric formulations and improve the wave estimates. Some of the meteorological storm scenarios describing the details of rapid wind shifts in frontal passages, tropical systems and explosively developing low-pressure systems could be better approximated.

The strong collaborative efforts between operational forecasting and wave research organizations in the Army/Navy Wave Prediction Group (Su et al., 1996) have made great strides in wave-modeling technologies and identified the areas where improvements can be made. Strong collaboration in wave-modeling efforts exists between the Navy and NOAA's National Center for Environmental Prediction because of the transition to WAVEWATCH III. Over the last decade, the errors in the wave forecasts have improved. Some of the improvements are generated from the continual improvement in atmospheric modeling technologies. However, a significant portion is realized using better wave models. There is still room for improvements, and field experiments such as SHOWEX, the Advanced Wave Prediction Program (ONR Programs), will provide the means to continually improve these results. The overall trend of bulk parameter errors in the ability to forecast the wave climate has decreased. Research initiatives are underway, pushing these third-generation wave models into arbitrary depths, and adding new and improved source-term mechanisms. New computational platforms are enabling increased complexity and spatial resolution in wave modeling technologies.

For global- and regional-scale wave forecasting, the ability to predict wave conditions in complex meteorological situations has become a reality. However, no wave model is perfect. Wave research activities continue to strive to increase the predictive skills used operationally. Enhanced wind fields, better wave model representations of the dynamics between the air and water surface and improved numerical schemes will provide the means to overcome the last 10 to 20 percent of the inherent errors found in present forecasting capabilities. The challenge of our wave research is toward that goal of producing the most accurate and timely wave forecasts one can possibly generate.

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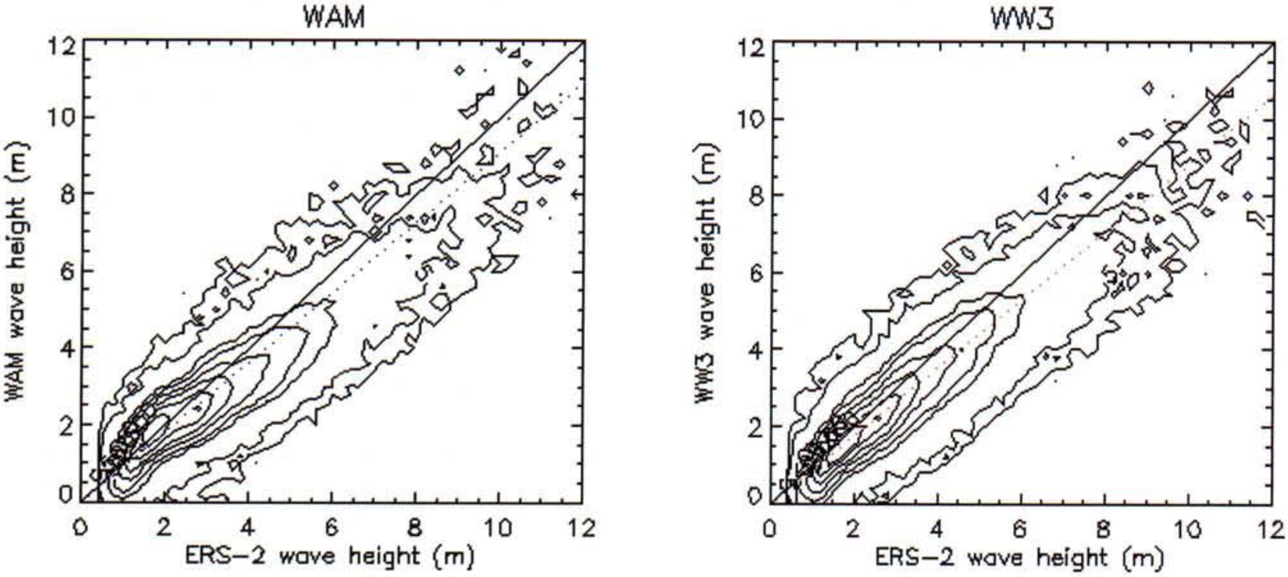

WAM/ERS–2 Error Statistics
Number of observations: 110191
Bias: –0.25
RMSE: 0.67
Scatter: 0.22
Cor Coef: 0.89
Symetric Slope: 0.91

WW3/ERS–2 Error Statistics
Number of observations: 110191
Bias: –0.33
RMSE: 0.64
Scatter: 0.19
Cor Coef: 0.91
Symetric Slope: 0.88

Figure 6. *Example of comparison between WAM* ***(left),*** *and WAVEWATCH III using ERS-2 satellite wave estimates for the month of February 2000.*

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